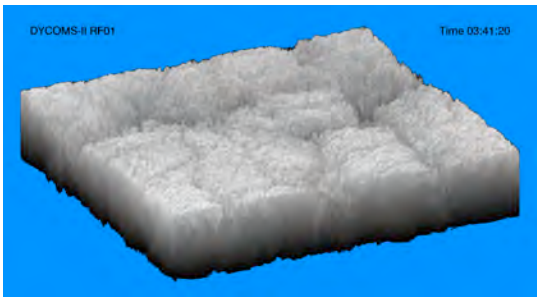
Center for Multiscale Modeling of Atmospheric Processes, Colorado State University
David A. Randall, PI; A. Scott Denning, J. Helly, C.-H. Moeng, and W. S. Schubert, Co-PIs
ATM-0425247

Tracking Parcels That Are Entrained Across Cloud Tops

Takanobu Yamaguchi

A marine-stratocumulus-capped boundary layer consists of a cloudy boundary layer, next to the Earth's surface, capped by an inversion layer in which the temperature increases upward. Cloud-top entrainment is a one way process in which free-atmospheric air is captured by the turbulence below. The entrained air becomes turbulent and cloudy through interactions with the boundary-layer air. Stratocumulus cloud-top entrainment is important because it affects cloud cover, cloud-top height, and cloud thickness. Our study is aimed at understanding how entrainment works.



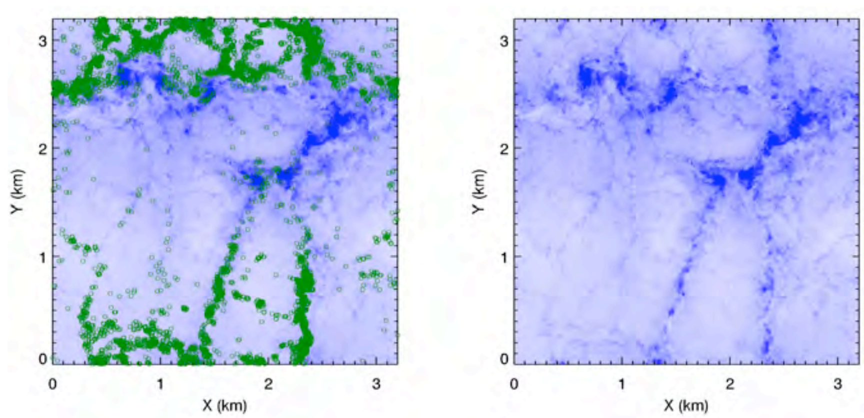
Simulated cloud field. Whiter color has larger cloud water. Narrow darker colors at cloud top are regions of sinking air.

The inversion layer acts as an interface between the free atmosphere and the mixed layer. The free atmosphere is warmer than the mixed layer air, so entrained air has to be cooled in order to enter the mixed layer. There are three ways that this can happen: infrared radiation, evaporation, and mixing. Analysis of data collected in observational studies suggests that infrared radiative cooling is the strongest of the three, but it is not possible to the processes at work during individual entrainment events, so assumptions have to be made.

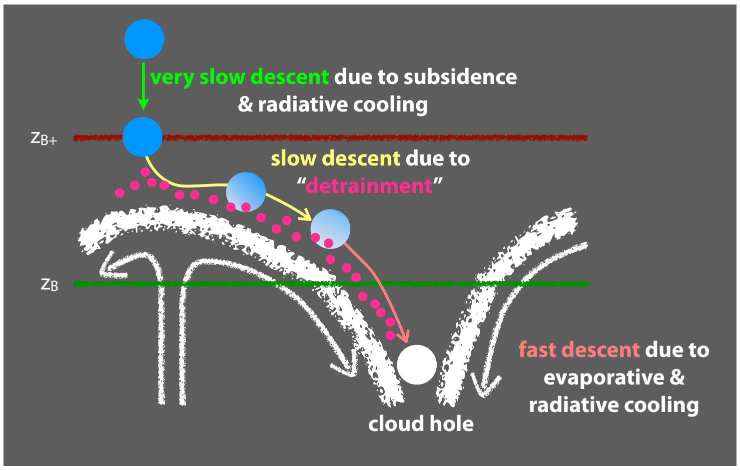
In this study, we diagnosed the buoyancy changes caused by infrared radiation, evaporation, and mixing, prior to and during entrainment. Their relative importance was assessed, through the analysis of results produced by a Lagrangian parcel tracking model (LPTM) coupled with a large-eddy simulation model that can be used to study turbulence. An LPTM predicts the positions of air parcels over time, by using the velocity field simulated by the large-eddy simulator, and makes it possible to focus on entrained air parcels; this is almost impossible to do in an observational study.

A nocturnal stratocumulus cloud was simulated using horizontal grid spacing of 5 m and a vertical grid spacing of 2.5 m. The run extended over four simulated hours. Over 40 million parcels were placed in the upper portion of the inversion layer and the lower portion of the free atmosphere near the inversion layer, then tracked during the simulation. Entrained parcels were identified based on their histories.

Conditionally sampled entrained parcel positions at the moment of entrainment, which is the first time when a parcel reaches the mixed layer, are superimposed on a cloud albedo image. Each green circle represents an entrained parcel. Comparison with the right plot shows that entrainment takes place at cloud holes, which are a dry sinking areas.



Analysis shows that entrainment occurs in particularly dry regions of sinking air. A mixing fraction analysis was used to separate the cooling rates due to infrared radiation, evaporation, and mixing. Results show that radiative and evaporative cooling are comparable (~0.2-0.7 K), but the largest contribution to buoyancy reduction comes from mixing (~8 K). The radiative cooling field is strongly inhomogeneous, and only weak cooling is found in regions of entrainment. As a result, the entrained parcels do not experience strong radiative cooling.



Schematic diagram illustrating the history of buoyancy changes for an entrained parcel. Levels z_{B+} and z_B represent the inversion base and mixed layer top, respectively.

Parcels descend slowly through the inversion layer, cooled mainly by mixing with wisps of air detrained from the cloud top. When the parcels have descended far enough to be influenced by the turbulence, they are carried towards the downdraft areas by convergent flows near the cloud top. Cooling due to radiation and evaporation accelerate their descent.

Our detailed analysis of simulated entrainment events suggests that evaporative cooling and mixing are more important than had been previously recognized. Our results will be used to improve the representation of stratocumulus clouds in climate models.